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Design Report

Title: Techno-Economic Assessment of an Advanced Regional Biomass Processing Depot – Case Study for the transition of the Bécancour Waterfront Industrial Park (Québec, Canada)

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Project Summary

This case study is on the transition of the Bécancour Waterfront Industrial Park (Québec) to a bio-industrial park. We are working on the implementation of a 2nd generation biorefinery in symbiosis to the Bécancour Park. The biorefinery would convert carbon-neutral sugar to high-value molecules such as chemical building blocks. The biomass supply will come from a decentralized network of regional processing depots tailored for the regional supply of corn stover and urban organic waste. We develop a corn stover-to-hydrocarbon (sugar) depot with an autonomous biofuel supply chain based on compressed natural gas (CNG) coming from a biodigester. The role of the depot is to process corn stover to dense, stable, and low-cost commodity sugar and co-products, compatible to the biorefinery and regional farms.

The depot is designed to process 180 DMg/d of regional corn stover, it will be in cohabitation with a pig farm, so no need for water treatment. The depot has many functions: (1) convert corn stover to carbon neutral carbohydrate (liquid cellulosic sugar); (2) used hemicellulose, C5, lignin and organic wastewater as animal feed; (3) enzyme unit production used free pulp and paper waste culture medium; (4) biogas unit treat swine manure and municipal organic waste (~80 DMg/d of different urban and farm residues); (5) digestate coming from anaerobic digestion used as soil amendments; (6) used of the CNG for all depot supply transportation.

The value chain is integrated and covers all steps of the production (field-to-depot-to-biorefinery); this model complexity implies a multilevel, multiscale, multi-temporal and multiplayer approach. The processing depot uses many types of biomass and covers many functions to create and deliver multiple value streams including carbon-neutral cellulosic sugar, alternative animal feed, renewable biomethane production, and efficient residual fertilizers recycle on farm.

Another side-business is dedicated to promoting good cultural practice on farm, this opportunity offers new value stream in close co-evolution with environmental issues and climate change. Depot will be located at strategic points in the regions to collect, transport, store and pretreat the biomass, into dense and stable intermediate products and commodities compatible to biorefinery at low-cost. The decentralized configuration of input-output flows minimize transportation needs and maximize synergies on transportation, this brings more economic and ecological benefits. To ensure an autonomous, low-cost, low-carbon and resilient supply system, all transportation would be based on self-product renewable CNG originating from the biodigester. The depot minimizes environmental impacts and could become the node for the promotion of good farming practices and low-carbon impact soil management.

As results, to obtain a net present value of zero for a 10% internal rate of return after taxes, the biomass depot can achieve a Minimum Sugar Selling Price of US$0.336/lb or US$888/Mg at the gate of the biorefinery, we pay all transportation. Currently, in 2017, the average price of the high dextrose syrup (95% purity), the U.S. “95 DE” is at

US$0.38/lb. These results show the competitiveness of our technology, it is now to see which form the business plan can take to maximize the benefits.

Introduction

We are studying the implementation of a second generation biochemical cluster, or biorefinery, in the Bécancour Waterfront Industrial Park. Figure 1 shows the potential synergy flows of materials and energy in the Industrial Park in Bécancour if a biorefinery was established. A biorefinery is the renewable equivalent of an oil refinery or petrochemical cluster. A biorefinery must integrate the entire value chain, so the upstream, midstream, and downstream process from the raw biomass to a spectrum of various products. The feedstock at the entrance can be from different sources of non-food materials such as residues from forestry, agriculture, aquaculture, industry, and households. This includes agricultural and forestry residues, energy crops, fast-growing trees, downgraded or unsold food, municipal solid waste, algae, etc. (Smith, 2014). The products at the output of the biorefinery should be a wide range of marketable products and energy. These products include materials, chemicals, feed, and food; while energy corresponds to fuels, power, and heat.

Since the 2000s, the market is gradually transitioning towards a bioeconomy. This latter is based on the use of renewable resources rather than using fossil fuels as feedstock. Renewable feedstocks are composed of various organic matter such as waste and by-products that can be transformed into various products (chemicals, food, and feed, materials and energy). Thus, the rise of the bioeconomy enables to limit our consumption of fossil fuel, in addition, to create sustainable jobs and prevent impacts on the environment, especially the reduction of greenhouse gas (GHG) emissions. It is easily conceivable to combine biorefining activities to industrial ecology approach to increase the added value of products by reducing cost on treatment, and transport, and increase local and regional development and environmental impacts. Industrial ecology is the fact that an industry exchanges their waste and by-products coming from a process, as raw material for another industrial process, in this way the industry limits its need on natural resources as well as its impact on the environment (Frosch & Gallopoulos, 1989). Indeed, a biorefinery would create new industrial synergies inside and outside of the industrial park. To ensure a quality and stable supply of biomass, regional processing depots adapted for corn stover, and urban waste would be set up in the regional landscape in order to generate more benefits for the communities and stakeholders.

Problems Addressed

The main objective of the work is to validate the concept of Regional Biomass Processing Depot (RBPD) model and assess the implementation of a depots network placed around the Bécancour Waterfront Industrial Park. The specific objectives are: 1) develop a techno-economic model of multi-purpose RBPD based on multiple works from the literature; 2) assess the depot model in the context of Bécancour and design a biomass supply chain tailored to the needs of local businesses and plants and a future biorefinery;

3) in a hypothetic case of a new bio-industrial park in Becancour with the implementation of RBPD(s) in the area, assess the economic, social, and environmental impacts associated with biomass recovery, transport, processing distribution and use.

The assumption of this study is that a decentralized supply chain in accordance with the concept of RBPD originally developed by Professor Bruce Dale from the Michigan State University is more efficient and generates more benefit than a centralized configuration. To make this assessment, this work develops a modeling framework to design a biomass supply system. The idea is to explore biomass value chain design in order to find the best value chain configuration to minimize the total operational cost and maximize the Net Present Value. The objective is to model the industrial operations so, we can compare and evaluate the performance of the model (supply chain, process performance, cost estimates of biomass and operating costs and balance mass-energy-GHG). Thus, we can assess the potential value creation of the project.

To do this, we need to find the optimal location for the depot, the best size and number of depots in the agricultural landscape, the optimal transport allocation of various flow, and the capacity of the biorefinery. This paper investigates the feedstock procurement cost, the transportation cost and the pretreatment cost and of the products. The problem can be stated as follows:

Given inputs data:

- Availability and location of the biomass feedstock and unit procurement costs for corn stover & urban waste
- Unit pretreatment costs at the depot depends on the biomass feedstock
- Transport logistics (cost, distance, capacities)
- Geographical distribution of coproduct demand area
- Set of demand over a fixed time horizon
- Capital investment costs

Determine the optimal decision variable:

- Geographical location of the biomass procurement sites
- Locations and production capacity (biomass depots & biorefinery)
- Allocation flows of each product between nodes
- Transportation network

Description of Biomass Depot

This case study is on the transition of the Bécancour Waterfront Industrial Park Québec to a bio-industrial park by the implementation of a 2nd generation biorefinery. The biomass supply will come from a decentralized network of Regional Biomass Processing Depot (RBPD) (see figure 2) based on the twin-screw extrusion technology. Depot will be located at strategic points in the regions in order to collect, transport, store, pre-process and pretreat the biomass into dense and stable intermediate products and commodities compatible to biorefinery at low cost. We design a corn stover-to-carbohydrate depot with autonomous biofuel supply based on compressed natural gas (CNG) coming from biogas originating from the biodigestion of slurry pigs and urban organic waste.

The advanced regional biomass depot processes agricultural residues (corn stover: stems, leaves, and remaining cobs) to produce cellulosic sugar that can be converted into high-value molecules. The depot is designed to process 66 k oven-dry megagram per year (DMg/y) of corn stover, and 28 k DMg/y of farms (pig manure), and urban and industrial organic waste (urban green residues, organic household waste, pulp and paper sludge and residues, saw mill wastes and phragmites australis). The depot works in synergy with a piggery farm and an anaerobic digester, so no need for water treatment and it will use the co-products on-site and locally as animal feed and energy use. Decentralized depot network fosters new industrial synergies between farmers and regional industries.

As we see in the Sankey mass balance diagram figure 3, the core business of the biomass depot is the production of the 21 k DMg/y of cellulosic raw sugar, renewable carbon neutral carbohydrates substitute for hydrocarbons fossil fuels. Second generation sugars that do not compete with food/feed crops that can be converted into several high-value products such as succinic acid (market value: US$2.5-3k/Mg), isobutene (US$1.9k/Mg), adipic acid (US$2k/Mg), citric acid (US$1k/Mg), ethanol (US$0.8-0.9k/Mg) (Taylor et al., 2015). This practice has several benefits on the environment; e.g. the BioAmber process in Sarnia, Ontario, generates 102.5% less GHGs as well as a 64.5% reduction in the amount of energy needed to make biobased succinic acid compared to the petrochemical analogous process. The production of 30 k Mg/y of biobased succinic acid reduces CO_2 emissions by 218 k Mg/y. We can think similar results in terms of GHG reductions for the case of Bécancour in the southern Québec region.

As side-business, the depot would produce 29 k DMg/y of hemicellulose and C5 dedicated to animal feed, 15 k DMg/y of lignin (47% used as heat and 53% for sales) and 24 k DMg/y of digestate. The co-products will be used as local animal feed, energy, and soil amendments. Also, the depot would produce 2.8 M m^3 of renewable biomethane (31% consumed for depot transport and 69% sold at CA$0.70/$m^3$). Self-production of biomethane allow to get lower transport costs, generate new revenues, secures and stabilizes supplies, and avoid the consumption of 2.3 M L/y of diesel fuel (representing 5.5 k Mg CO_2/y).

Geospatial database

Geographical information systems (GIS) is a powerful tool to characterize a territory and build maps that identify suitable locations to implement biomass depot. Building a geodatabase requires multiple packages of raw data, i.e. the biomass availability, the animal distribution, and other spatial components (roads, urban area, land-use, etc.). For this purpose, we used the Biomass Inventory Mapping and Analysis Tool (BIMAT) which is a raster cell of 10-km distributed by Agriculture and Agri-Food Canada (AAFC, 2008). Each cell represents the inventory information of the annual corn stover available shown in dry metric tonne. The precise location of the feedstock is represented by the centroids of the cell. Agricultural information of BIMAT is based on the annual corn crop production between the period 1985-2010. Also, the Québec Government's Ministry of Agriculture, Fisheries and Food gave access to geospatial data of the animal distribution of the livestock units in the southern Québec. These data are represented in a multipoint shapefile with the number of pig heads per farm and their respective coordinates (MAPAQ, 2017). Finally, the Québec Government's Ministry of Energy and Natural Resources gave access to the theoretical potential and the spatial distribution of the available urban organic waste (in dry metric tonne per year) (MRNQ, 2012). The method to calculate the theoretical potential is based on the demographic distribution (ISQ, 2015) multiply by the per capita generation of residual organic waste (RECYC-QUÉBEC, 2009).

Methodology – GIS location & allocation flows for biomass depot

Once the geodatabase is built the methodology is applied to locate the biomass depot and the optimal allocation flows is in three steps: (1) Geographical information system – Multi-Criteria Decision Analysis (GIS-MCDA), (2) the network analyst in ArcGIS, and (3) the allocation solver in Python for the three-step supply chain with two transportation arcs: (a) Feedstock origin, (b) Intermediate processing hub, (c) Biorefinery destination.

The suitability analysis is built in ESRI ArcGIS, GIS-MCDA is a popular method to know the best spots to implement a facility. The suitability analysis is based on these steps: (1) a Restriction analysis which represent the place where we can not implement a biomass depot, then (2) a Suitability analysis which are the best spot to implement a depot, according to various criteria with specific weight we develop, (3) these weights have been determined using an Analytic Hierarchy Process in Expert Choice software. The criteria are: (a) biomass availability, (b) animal distribution, (c) proximity to CNG demand, (d) proximity to urban areas (e) proximity to Bécancour, (f) proximity of roads.

Thereafter, in the GIS Network Analyst, we develop the Location-Allocation Model. We used the results of the suitability analysis to perform the Location-Allocation analysis in ArcGIS for developing optimization models by the calculation of the supply chain configuration. The purpose is to minimize the transportation cost. So, we identify the locations of potential depots according to the least cost routes (or the minimum impedance pathway) for the transportation. We compare different supply chain configuration according to the type of feedstock, number of depots and the availability of the biomass in the territory.

Finally, the optimization of the allocation model is built in Python with a library named PuLP. The optimization package is linked to the solver COIN-OR which is an open source optimization models (including LP, simplex solver, combinatorial problems, etc.). Coin-OR is used to optimize the allocation of flows to maximize demand while minimizing cost, without violating the constraints on flow. Optimizer develops maps and spreadsheet data reports.

The results of this three-step process represent the optimal location and allocation for the biomass depot, it can be seen on the map 1.

Feedstock logistics and pretreatment process

Feedstock logistics include operation at-field, the storage, and the transportation to move corn stover to the intermediate processing depot. The main operations are: the feedstock harvesting and collection, the storage on field edge under plastic tarp, and the transportation.

The harvest method for corn grain used a combine harvester. Corn stover is chopped and raked in order make baled. Fall is the usual harvesting season for the corn stover in Québec. According to the harvest time in the season the moisture content (M.C.) could vary 15-35% (Li & Khanal, 2016; Lépine, 2009). The crop can be baled using a round baler or a square baler system. The storage strategy is developed in two stages : (1) outside long-term storage (maximum of 11 months), where biomass is dried and stored in piles of 5,000 Mg (~10.4 k m^3) in the fields under a waterproof sheet and a concrete slab. Then (2) the short-term storage the depot involves a steel structure with soft canvas with a moving floor. About 1,500 Mg of biomass can be stored there.

The biomass pretreatment includes fractionation by coextrusion, a separation by filtration, enzymatic hydrolysis, purification and concentration of sugars. First, fractionation by twin-screw extruder aims an optimal sorting of the cellulose streams, and then hemicellulose and lignin can be sorted by filtration to facilitate their valorization. This unit can use chemical treatments with high temperatures. The combined action of the temperature and pressure and the mixing effect by the double screw accelerates the rate of chemical reactions. The greatest advantage of this pretreatment technology is the flexibility of usage for the input feedstock, the transformation process, the products at the output and the volumes that can be processed. The next parameters are the most influent: dimensioning of the units, operating temperature, residence time, consistency of the biomass at the entrance, the rotation speed of the screws, and quantity and type of chemicals added (NaOH, KOH, H_2SO_4). Then, the enzymatic hydrolysis is used to break the long chains of sugars that make up the cellulose to obtain basic monosaccharides. This technology enables to use the cellulose in order to convert them into high-value dextrose. The conversion of sugars would be performed using a cocktail of enzymes, Accellerase® 1500, developed by DuPont Industrial Biosciences. Afterwards, the purification and concentration of sugars require the separation of fermentation inhibitors by membrane filtration. Subsequently, the concentration of sugars is done by the extraction of water by membrane filtration in order to increase the sugar density. Once the sugars produced, the last step would be the fermentation, which is the transformation of sugars into alcohol. But, in the case in Bécancour this step would be supported by the biorefinery. So, cellulosic sugars (or molasses) would be directly shipped by transportation to the biorefinery.

The enzyme inoculation technology from DuPont Industrial Biosciences would serve to produce in situ enzymes on the operating site, in small production units for local or on-site uses. Enzyme production could use a variety of growth medium such as the organic waste from the production of the depot, local paper mill sludge, and whey from the dairy industry. The medium would be sterilized and then inoculated in a series of steps.

The C5 stream, derived from the hydrolysis of hemicelluloses, and the proteins can be valued as grains for the animal feed, without drying. Also, the other coproducts of the pretreatment can be used as grains because they contain vitamins, proteins and nutrients. The lignin is a complex polymer derived from fractionation of biomass during the coextrusion. The lignin is the most abundant and sustainable source of aromatic compounds. The lignin is waterproof and antifungal. His availability makes it a good alternative as a durable material, particularly in the building industry. Also, lignin can be valued as high-efficiency energy pellets. Indeed, when dried at 70% and pelletized, lignin has an energy density of 24.4 GJ/Mg.

Techno-Economic Analysis – Minimum Sugar Selling Price

The following analysis described a techno-economic model that estimates the Minimum Sugar Selling Price (MSSP) for a commercial process. The results are uncertain, depending on the assumptions of the capital and operating costs. “The discounted cash flow rate of return (DCFROR) analysis estimates the minimum price that satisfies the condition that the net present value of the project is zero.” (Kim & Dale, 2015). The purpose of developing a process design with a cost model is to determine the economic value of the production. This information can be used as a product cost potential indicator in comparison with the market and guide decision-making and further research. Indeed, Break Even Selling Price can use as a tool “to assess the marketplace competitiveness of a given process, it is best suited for comparing technological variations against one another or for performing sensitivity analyses that indicate where economic or process performance improvements are needed.” (Humbird et al., 2011).

According to Humbird et al. (2011), the first step of the DCFROR is to determine the total capital investment (TCI), i.e. direct and indirect overhead cost factors such as equipment and installation costs. The second step is to determine variable and fixed operating costs such as the supply chain operations, transport, biomass purchase price to farmers or biomass owners, etc. “Corn stover price at the farm gate is estimated based on fuel costs for collecting and baling corn stover, field operating costs (e.g., farm machinery cost, labor, etc.), and costs for additional nutrients in the subsequent growing season due to removing nutrients in corn stover (i.e., nitrogen, phosphorus, and potassium).” (Kim & Dale, 2015).

Parameters used in this analysis will be obtained from assumptions and literature. Thus, this information will be estimated and integrate into a Microsoft Excel spreadsheet. In more details, the economic assessment of a biorefinery contains these steps: (1) Design a process flow diagram, (2) Calculating mass and energy flows, (3) Sizing major equipment, (4) Estimating the capital cost, (5) Estimating the production cost, (6) Forecasting the product sales price, and (7) Estimating the return on investment (Khachatryan et al., 2009).

The aggregation of the cost data allows performing the DCFROR to determine the plant-gate price for raw sugar at a given discount rate. This plant-gate price is called the Minimum Sugar Selling Price (MSSP), required to obtain a net present value (NPV) of zero for a 10% internal rate of return (IRR) after taxes. This information gives the economic performance of the biomass supply chain with the depot technology, and give the possible profitability range. Knowing the MSSP is the main purpose of this work, thus we can compare the technology of the depot with the current sugar market price in US and Brazil.

Also, this analysis requires income tax rates, a depreciation method, plant life, and construction cost and duration. This plant is equity-financed, so assumptions on loans are required. This type of "analysis does not take into account any policy factors such as subsidies, mandates […] because these would be purely speculative. The purpose of this analysis is to demonstrate whether or not cellulosic [sugar] can be cost-competitive on its own merits and, if it cannot, to give policymakers a sense of the magnitude of incentive required to make it so." (Humbird et al., 2011).

The mathematical formulation of this function is represented in this equation, the purpose is to find the Minimum Sugar Selling price (MSSP) (SP). We balance the left-hand side of the equation to obtain a Net Present Value (NPV) of zero US$ (2011) for a 10% internal rate of return (IRR) after taxes.

$$ZERO\ NPV = \ -TCI + \sum_{t=-2}^{30} \frac{SP_t Qs_t + HP_t Qh_t + LP_t Ql_t + MP_t Qm_t - SCC_t - OC_t - ID_t - IHT_t}{(1+IRR)^t}$$

where:

TCI: Total capital investment;
$t \in \mathrm{T} = \{-2,-1,0,1,2,3 \ldots 30\}$ is the year of operation with 3 years for construction;
SP: Sugar price (US$) at depot-gate product during year *t*;
Qs: Sugar production (Mg) of depot during year *t*;
HP: Hemicellulose price (US$) at depot-gate product during year *t*;
Qh: Hemicellulose production (Mg) of depot during year *t*;
LP: Lignin price (US$) at depot-gate product during year *t*;
Ql: Lignin production (Mg) of depot during year *t*;
MP: Biomethane price (US$) at depot-gate product during year *t*;
Qm: Biomethane production (Mg) of depot during year *t*;
SCC: Supply chain cost (US$) of depot during year *t*;
OC: Operating cost (US$) of depot during year *t*;
ID: Interest and depreciation (US$) of depot during year *t*;
IHT: Insurance, housing and taxes (US$) of depot during year *t*;
IRR: Internal rate of return

Social and Economic Design Benefits

The project outcomes would affect social and economic aspect. The implementation of a network of biomass depots would use agricultural residues and that would promote value creation and economic diversification of the region. Farmers would benefit of new incomes that would stimulate the development and boost local economies by creating jobs in rural areas.

On the social innovation, an important benefit of the implementation of a biomass industry is the employment opportunities related to the economic development at regional and local scale. The implementation of the biomass cluster in rural areas is a good asset that creates green jobs and decreases the phenomenon of rural exodus. Indeed, value creation and new incomes for farmers encourage young people and intergenerational transfer of the land. These innovations contribute to social cohesion and stability and help to reduce rural exodus.

The implementation of biomass industry cluster would partly counter the agricultural land grabbing for speculative and strategic investment. This would ensure the permanence of the farmland occupation by residents as well as a safe food supply in the long term. The presence of a biorefining cluster would provide a secure supply of renewable resources and energy in an uncertain context of fossil fuel depletion. Biomass industry fosters energy security as it shifts the need to resort foreign oil products. Also, it is an asset for farmers to provide an alternative income security in case of agri-food crops destruction due to climatic and environmental extreme events.

Good Cultural Practice

Currently, the biomass depot allows the good management of 24 k DMg/y of digestate used as residual organic fertilizers recycle on farm. Applications of digestate on land will require less labour and machinery, that will help to promote good cultivation practice. On medium term perspective, the depot could be coupled to an algae cultivation ponds as well as a wetland filter in order to reduce the amount of liquid in the digestate. The farmer could obtain a digestate with lower humidity, and at the same time less transportation cost. The production of algae will provide an extra protein supply and nutritional supplements (e.g. omega 3 & 6) to the diet of pigs. The biomass produced by the herbaceous plants in the wetland will be used as an on-site production feedstock for the biodigester (see figure 2).

The depot fosters the take back of organic C & N into the soil and promotes their sequestration, a practice that is in development and encouraged. Ultimately, the depot could become the node of promoting good agricultural practices and low-impact soil management on GHGs. A smart management of the agricultural soils in Québec is essential; we need to encourage simultaneous production of food, feed, and fuel without competition and land-use change. This requires diversification and popularization of good agricultural practices helping regenerate the humus, foster the storage of organic C & N into the soil. This can be done through crop residue management, avoiding the bare soil, limiting carbon losses, developing intermediate crops and intercropping that fix N, promoting agroforestry, green manure spreading, minimum tillage and adding into the soil residual organic fertilizers (digestate, manure, and compost). e.g. intermediate crops (leguminous) are a nitrate trap which reduces emissions of N_2O, a powerful GHG with a warming potential 300 times greater than CO_2. Good practices promote nutrient recycling, reduce GHG emissions and reduce the costs of mineral nutrient intakes. Several other practices can be developed such as avoiding tillage, foster direct seeding that can be under cover with a cover crop that stores C & N, which contributes to the porosity and keeps good soil moisture. This contributes to the good drainage, fill the aquifers and helps to keep waters upstream to reduce the risks of flooding, reduces wind erosion and leaching, and gives more resistance against droughts.

Encouraging good farming practices (no tillage, windbreaking hedges, riparian strips, etc.) help the conservation of the natural environments and contribute to sustainable development. Reduction of tillage keeps the carbon into the soil and avoided the release of GHGs into the atmosphere. Indeed, to carry out tillage, it is necessary to use a tractor, which consumes a large quantity of fuel and which emits GHG. The implementation of windbreak hedges reduces the speed of winds, thus protecting the soil loss caused by wind and water erosion. A tree hedges also foster to trap snow and to ensure a good recharge of the underground aquifers, and the wood can serve as an energy and material resource (UQCN, 2005). A good living organic soil is an important asset for a healthy agriculture.

Environmental Benefit Opportunities

The development of a biorefinery based on cellulosic sugars and co-products would have many environmental benefits because biomass is a renewable and sustainable resource, if well managed, their use extends the actual reserves of fossil fuels. Biomass has many benefits; it is a renewable resource, and it reduces greenhouse gas emissions. In fact, biomass is considered as renewable and carbon neutral because it is the result of the conversion of the solar energy by photosynthesis into usable material and energy. The CO_2 released when biomass is burned is balanced by the CO_2 captured when the plant grows. This differs from petroleum, which is made from plants that grew millions of years ago. On a life cycle analysis basis, the use of cellulosic biomass could reduce GHGs and other air pollution by producing less ozone precursors, emits less CO, CO_2, SO_x and NO_x, less sulfur dioxide, benzene, and butadiene, and has lower volatility and photoreactivity.

There are several environmental benefits to the implementation of a decentralized biorefinery with a depot supply network: (1) that replaces fossil fuel with renewable vegetable carbon neutral sugars, (2) that diversifies and reduces the cost of animal feed, (3) that self-produces sustainable biomethane that replaced fossil fuel for transportation, which reduces supply costs, reduces GHG emissions and stabilizes fuel supply, (4) that promotes new and uncommon industrial synergies between farmers and regional industries. Also, according to Dale et al., (2014) and Eranki et al. (2013), biomass use can be benefit for the environment (air, soil, water), but it must be carefully calculated because not all feedstocks are environmentally friendly. The best type of feedstock to valorize is the “waste” biomass coming from agricultural and forest residues, or various organic processing waste.

Moreover, the inclusion of algae biomass production and herbaceous plant at the depot allow to reduce the amount of water in the digestate; thereby reducing the quantity of tanker trucks on the road. The densification of digestate reduces the transportation, so less GHG emission and less compaction in the fields. Also, an on-site production of algae rich in protein and fatty acids contribute to improving the nutritive quality and health of pigs (Plourde, 2005; Shackford, 2012). Also, this practise contributes to a sustainable, autonomous and low-cost animal feed supply.

Another environmental benefit of the biomass use is related to the implementation of best practices in farmland management and feedstock supply. As mentioned, it increased soil organic carbon, reduced soil erosion, reduced nitrogen and phosphorus loss fertilizer and leaching/emissions, improved crop water use efficiency and water quality. It also helps to increased biodiversity and wildlife habitat.

Costs – fixed assets & operating costs

This study assesses the economic performance of a decentralized cellulosic biorefinery with a supply network of Regional Biomass Processing Depot (RBPD) in terms of minimum sugar selling price (MSSP). Indeed, once the total capital investment, variable operating costs, and fixed operating costs have been determined, a discounted cash flow rate of return (DCFROR) analysis can be used to determine the MSSP and thus assess the economic viability of the project. Assuming a partly develops site to retrofit for mixed usage in cohabitation with a pig farm and an anaerobic biodigester.

The Techno-Economic Analysis (TEA) shows, as we can see in figure 4, sugar represent 73.6% of the income, the TEA also focuses on the impact of the revenue on the co-products stream for a biomass depot. This process considered three commercially viable co-products: (1) animal feed that represent 11.1% of the income, (2) biomethane in the form of compressed natural gas 5.2% of the revenue (CNG), and lignin 2.6%. This profit margin is about US$ 5.2 M/y almost 28% of the total revenue. Figure 4 shoes the expenses, feedstock cost remains the largest cost item (23.5%) within the TEA, followed by the collection cost (16.7%), and the transportation input-output (15.3%), the pretreatment (11.6%), personnel (10.5%), annual depreciation, (8.7%), etc.

As economic results, to get a 10% Internal Rate of Return after taxes, the Minimum Sugar Selling Price (MSSP) would be about US$0.336/lb or US$888/Mg at the gate of the biorefinery, we pay all transportation. In 2017, the average price of the high dextrose syrup (95% purity), the U.S. “95 DE” wholesale dextrose is at US$0.38/lb[1], with the delivery cost from Brazil (US$ 0.043/lb[2]), the total is US$0.42/lb. These results show the competitiveness of our technology, it is now to see which form the business plan can take to maximize the benefits.

Regarding the value of the fixed assets, as we can see in figure 5, the total investment capital of the depot, including the inside battery limits, installation, direct costs, contingency, etc. would be about of US$(2011) 51.5M or US$(2017) 56.2M or CA$(2017) 70.1M. The total inside battery limits (ISBL) would be about $US(2011) 7.7M and the total installation cost of equipment would be $US(2011) 31.2M.

We performed a sensitivity analysis to identify the critical parameters, assess the viability, and reduce the uncertainties of the project. As result, we can say that the most critical parameters to affect that NPV is first the sugar yield and market price, then the target ROI select, and the corn stover price access to the farmer, and then the feed price, loan interest, electricity price, CNG price, and finally the initial equity.

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[1] Source: Milling & Baking News.

[2] World Freight Rates (WFR). www.worldfreightrates.com

Regarding the new income for farmers, the increase in the margin related to the corn residue harvest gives participating farmers about CA $ 31.22/Mg (M.C. 15.5%) or an average of CA $ 72.25/ha. This includes the purchase of raw material ($ 13.03/Mg), the compensation for to field border cost and storage cost ($ 8.33/Mg), and the nutrient removal compensation ($ 9.86/Mg).

Implementation Challenges

There are many constraints and challenges to the development of the bio-based economy such as the availability of the biomass feedstock, the cost of the supply chain and the sustainability of this new industry. Biomass industry strongly depends on the logistics and the local conditions of production of the feedstock (Kim & Dale, 2015). To get over these barriers the industry must be efficient especially by the optimization of the supply chain configuration (Yue, You, & Snyder, 2014) and the management of the co-products.

Biorefinery value chain requires many components upstream and downstream of biomass conversion process. Every biorefinery project must pursue specific market opportunities as well as aim to meet environmental and social targets established by government, public, private sector and other stakeholders. To understand the impacts of biorefinery operations, the three major steps in the production chain need to be assessed. These steps are biomass collection and preparation, biomass conversion to final products, and distribution and sales to customers.

First, the targeted biomass needs to be evaluated depending on its quality, availability, and other characteristics such as GHG intensity. Various collection and preparation strategies can be developed to link the feedstock properties with biorefinery design. Second, the choice of conversion technologies selected for a biorefinery is dictated by feedstock properties and targeted products. Third, the biofuels and bioproducts are distributed to the final consumers to meet their economic, social, environmental, and legal goals and requirements. Furthermore, all these steps and objectives are impacted by policies and regulations enacted by local, provincial and federal governments.

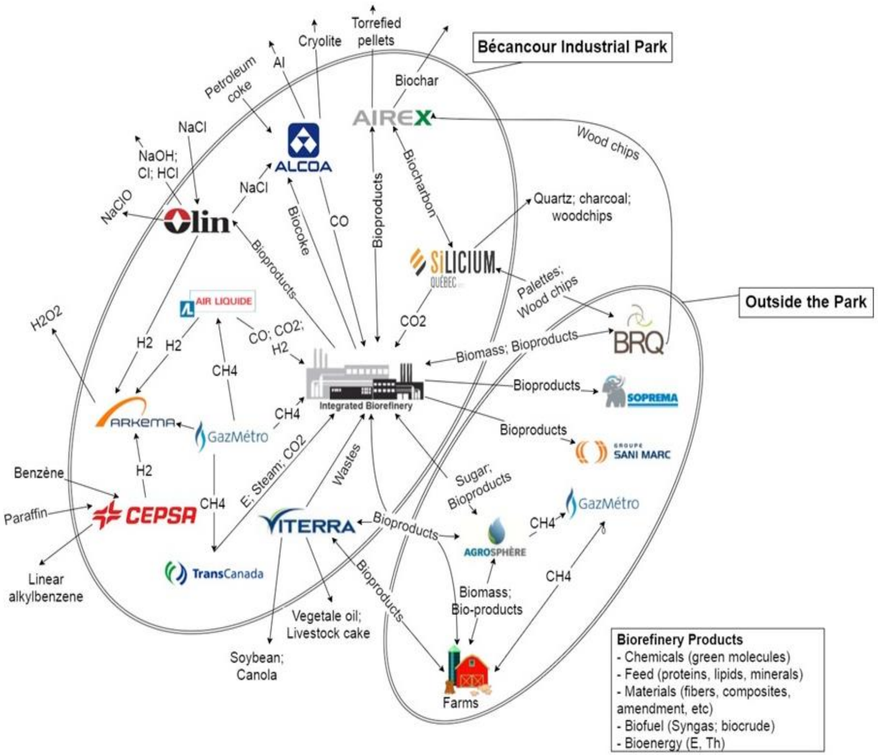
A biorefining project must be done when it can be beneficial to the community. But to do this, it must be tailored to the local and regional needs and realities to offer a maximum of benefits to the community. Many criteria must be considered such as the quality and the quantity of the organic matter (wood, agricultural, industrial residues, municipal solid waste, sludge, etc.) into a small supply radius. An integrated biorefinery must consider local infrastructures and opportunities to revitalize and develop local communities. Extracting and transforming technologies must be adapted to existing infrastructure. Biomass must be secured between the users and suppliers with contracts on long-term. All the upstream steps (harvest, handling, fractioning, pretreatment, etc.) before the refining process are important to maximize value. Just as transportation logistic between users and suppliers. Biomass products and co-products must be adapted to the on-site and local needs.

According to Marciano et al. (2009), the biggest challenges are the local concerns such as the truck traffic, exposure to noise, odor and other kinds of nuisances. Likewise, another concern of the inhabitants is the industry's impact on the organic resources (forest, agriculture, etc.) linked to the ecosystem services (provisioning, regulating, supporting, etc.).

A good strategy to successfully collaborate with the local communities is the transparency. There are many positive impacts to the implementation of a biorefinery. It is important to communicate this information to the community. The benefits are in the rural and regional development, in the employment, and the environment. Concretely, a biorefinery stimulates job creation, diversify the economy, and maintains forest ecosystem values (water quality, wildlife habitat, and soil nutrients).

Finally, having access to GIS data such as the animal distribution and biomass availability is a challenge because these data are owned by the Canadian and Québec governments. We needed to officially request the data, having approval, follow up on files, etc. it took a year to have the data of biomass availability from the Ministry of Natural Resources and Wildlife and it took another year to have the data from the Ministry of Agriculture, Fisheries and Food.

Figures and Tables



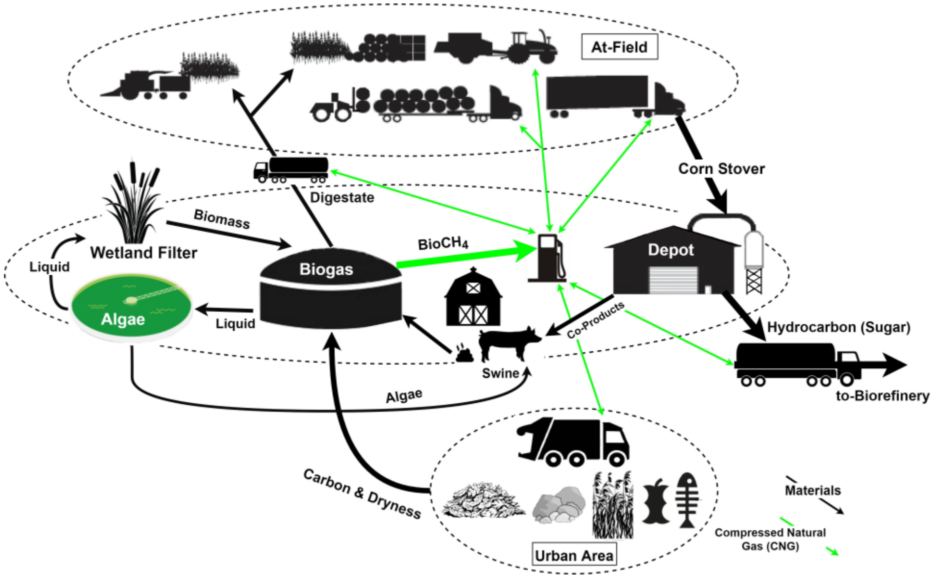


Figure 1 – illustrates the potential flows of materials and energy into the Waterfront Industrial Park in Bécancour if a biorefinery was implemented. «Biorefinery would create synergies into the park, but also outside of it. Indeed, to ensure a quality and stable supply of biomass, regional processing depots adapted for agricultural biomass could be set up into the region in order to generate more socio-economic benefits for the communities and stakeholders.

Figure 2 – Advanced multi-biomass and multifunction depot in synergy with a pig farm and an anaerobic digester. The proposed design of the corn stover sugar depot with autonomous biofuel supply based on CNG (compressed natural gas) coming from biogas originating from slurry pigs and urban organic waste. The depot is designed to process 180 DMg/d of corn stover, and biodigest 80 DMg/d of farm and urban organic waste. Depot will be in synergy with a pig farm, so no need for water treatment and we will use the residual lignin to dry the raw sugar before shipping it to the biorefinery.

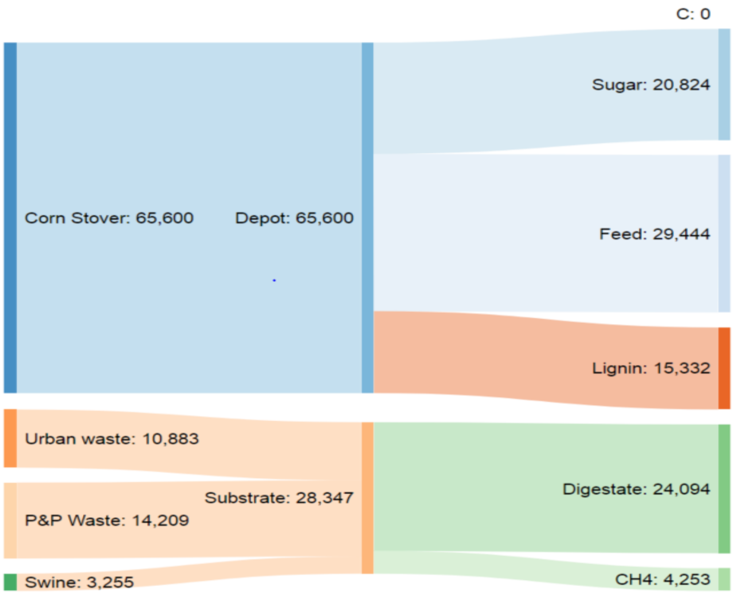


Figure 3 – Sankey diagram of material balance process input-output (Natural gas: 2.8 M m^3/y (30% transport, 70% sold); Avoided CO$_2$: 5.5 k Mg CO$_2$/y).

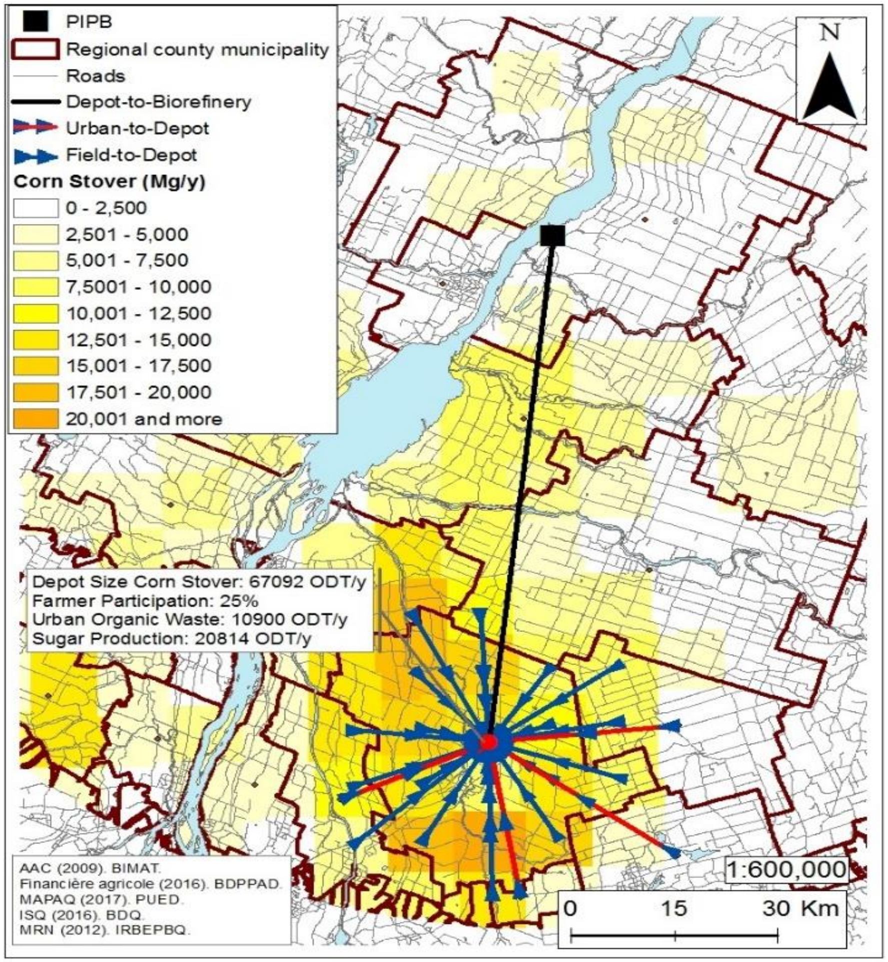


Figure 4 – MAP GIS-based assessment of the Bécancour (Québec, Canada) biorefinery Supply System – Optimum Location, Allocation and Farmer Participation. The map represents the supply network composed of arc flows and nodes. The node is the regional biomass processing depot and the black square is the biorefinery. Various materials are transported between these nodes: the raw biomass (corn stover is in blue and urban waste is in red), the cellulosic sugar (in black) and the coproducts (hemicellulose and lignin).

Expenses		
Costs	US$/y	%
Cost of feedstock	3,154,656	23.5%
Cost of collection	2,244,086	16.7%
Pre-treatment costs	1,556,958	11.6%
Personnel costs	1,405,617	10.5%
Transport input	1,207,052	9.0%
Transport output	841,579	6.3%
Biogas production	683,208	5.1%
Annual Depreciation	1,166,126	8.7%
Maintenance, Property insurance & Tax	591,052	4.4%
Loan Interest Payment	346,999	2.6%
Government taxes	212,905	1.6%
Total cost	**13,410,238**	**100.0%**

Revenue: Products & Co-products		
Material	US$(2011)/y	%
Sugar	14,152,627	73.6%
Animal feed	2,130,085	11.1%
CNG biomethane	1,003,840	5.2%
Avoided diesel use	646,936	3.4%
Lignin	491,290	2.6%
Phragmites elimination	349,730	1.8%
Digestate	237,913	1.2%
Avoided CO_2 biodigester	227,482	1.2%
Total revenue	**18,592,968**	**100.0%**

Figure 4 – Cost & Revenue Division (US$ 2011)

Total Capital Investment	**2011 Dollars**
Land 000	$596,877
Handling & Storage 100	$1,288,709
Pretreatment & Water 200-300-400	$2,827,838
Enzyme 500	$338,355
Coproduct & Building 600	$1,398,619
Biogas 700	$1,242,532
Other equipments	$2,616,432
Installation	$20,933,910
Total Inside battery limits (ISBL)	**$7,692,930**
Total Installed Equipment Cost	**$31,243,272**
Warehouse	$230,788
Site Development	$346,182
Additional piping	$346,182
Total Direct Costs (TDC)	**$32,166,424**
Indirect Costs	
Prorateable Expenses	$3,216,642
Field Expenses	$3,216,642
Home Office & Construction Fee	$6,433,285
Project Contingency	$3,216,642
Other costs	$3,216,642
Fixed Capital Investment (FCI)	**$51,466,278**
Working Capital	$2,573,314
Total Capital Investment (TCI)	**$54,039,592**

Figure 5 – Total Capital Investment in (US$ 2011)

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